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INTEGRATING SPHERE MEASUREMENTS OF DIRECTIONAL-HEMISPHERICAL TRANSMITTANCE OF WINDOW SYSTEMS

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ABSTRACT

Equations are presented that express the directional-hemispherical transmittance of window systems in terms of the experimental parameters of an integrating sphere. The construction and operation of a 2-meter-diameter sphere is described. Experimental results are given for both conventional and novel window systems.

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INTRODUCTION

Measurement of the directional-hemispherical transmittance of a fenestration system is important because the total radiant or luminous transmitted flux affects the daylighting and thermal performance of the system. For daylighting calculations, the single most important optical property is the hemispherical transmittance, which is required for any calculation based on the lumen method. For more detailed analysis of illuminance distribution, the bi-directional transmittance is required. These properties can be calculated from first principles for simple fenestration systems consisting of one or more homogeneous glazing layers. However, as glazing materials become more diverse, as geometrically complex shading devices are introduced, and as sophisticated architectural light control solutions (e.g., light shelves) become more commonplace, it is increasingly difficult to calculate directly the required properties. Similar comments apply to solar heat gain factors and shading coefficients, which are two related measures of the solar heat gain introduced by window systems. Furthermore, daily, monthly, or even annual average properties, often used for energy calculations, may no longer be adequate to analyze conditions in daylighted spaces when hourly energy use simulation models are used. These computer programs require solar-optical properties that adequately characterize glazing transmittance under all sun and sky conditions.

To meet these new data requirements, we are developing a series of interrelated calculation methods and new measurement techniques to fully characterize the daylighting properties of fenestration.[1] We use two computer simulation tools: Superlite, an illuminance model, and DOE-2, an energy simulation model. There are links between the programs, and each is supported by data from experimental facilities, such as a hemispherical sky simulator used to measure illuminance distributions in scale models.[2]

This paper describes the development, operation, and initial results from an integrating sphere used to determine the directional-hemispherical transmittance of glazing materials, fenestration systems (including complex shading devices), and building envelopes or facades (in scale model form). Because of the complex spatial distributions of light transmitted by even relatively simple window systems, a sphere is required for making transmittance measurements. With a single measurement of its interior illuminance, the integrating sphere provides information equivalent to the sum of many luminance measurements spanning the hemisphere into which the test sample is transmitting.

When luminous flux having an arbitrary spatial distribution excites the diffusely reflecting inner surface of a sphere, a detector in the sphere measures illuminance proportional to the flux and independent of position on the sphere surface.[3] The sphere integrates and averages the flux from a source independent of its particular spatial distribution. This geometric property of the sphere has been made use of in several ways. Historically, the sphere was first used to measure the luminous output of lamps situated within itself. No matter what the particular spatial distribution of flux from a lamp, the sphere illuminance is proportional to the total flux, and can be compared to its value from a standard source.

Another use of the integrating sphere is to determine the directional-hemispherical reflectance of a sample placed inside it.[4,5] In this application a light beam from an external source is introduced into the sphere and reflected by the sample to become the excitation flux striking the sphere. Comparison of the resulting illuminances when a sample and a standard are alternately illuminated enables determination of the sample's reflectance. The incident flux is directional because the source has a specified angle of incidence with respect to the sample/standard. The sphere integrates the flux reflected over the entire hemisphere surrounding the sample/standard.

We present results from another application of the integrating sphere, determining the directional-hemispherical transmittance of a device that is placed over a port in the sphere, and then illuminated by a uniform exterior source. This technique has been used to measure the transmittance of small homogeneous samples.[6,7] When we began this project in 1981, we believed it to be the first time an integrating sphere was used to measure the transmittance of large non-homogeneous glazing. Recently we discovered that a sphere of similar size had been used to measure the optical properties of glass block in 1951.[8] Figure 1 illustrates the experimental arrangement and shows how rotations about three axes are used to produce an arbitrary altitude and azimuth for the source. Figure 2 shows the sphere in use.

THEORY

For a perfect sphere of radius R, having no ports or internal obstructions, the measured illuminance, E, can be written $E = (\Phi/4\pi R^2)(\rho / 1 - \rho)$, where ρ is the reflectance (perfectly diffuse) of the sphere, and Φ is the excitation flux.[3] Hisdal[5,6] applies a finite-difference-equation flux-balance method to obtain expressions for the directional-hemispherical reflectance (of a sample mounted against the wall of a sphere) in terms of the sphere and port radii, and sphere wall reflectance. We have extended this method to obtain the directional-hemispherical transmittance:[9]

$$T(\theta,\phi) = (E/E_0)(\Phi_0/\Phi)\left[1 - r_1 C'\right], \tag{1}$$

where θ,ϕ are the altitude and azimuth of the source (relative to the normal of the sample); E and E_0 are, respectively, the illuminance measured with the sample, respectively, mounted, and dismounted; Φ,Φ_0 are the fluxes incident on the port at the instant of measurment, with sample, respectively, mounted, and dismounted. Note that this definition of T allows values greater than unity, as for example, if the device incorporated reflectors to increase the "effective" area of the port.

The right-hand bracketed term is a correction factor, C, that accounts for the higher illuminance readings when the device, with its non-zero reflectance r_1, is substituted for the zero-reflectance open port. The correction factor is equal to $1 - r_1 C'$, where r_1 is the sample reflectance (as viewed from within the sphere) and C' is a constant that depends on the reflectance of the sphere wall, r_2, and the ratio r/R of port to sphere radius. For our 2-m-diameter sphere, the factor C' has the value 0.09 with 0.50-m-diameter port in place, and 0.15 with a 0.69-m port. We have experimentally confirmed this correction factor using specially constructed samples of known transmittance and reflectance. The sample reflectance, r_1, may be measured by methods described in the literature.[10] Frequently, a directional-hemispherical reflectance is used in place of the hemispherical reflectance.

CONSTRUCTION

Because our intended application is to develop a data base of properties of complex fenestration components, we require a relatively large sphere. Construction began with a 2-m-diameter spherical tank made from high-density cross-linked polyethylene. The sphere was cut in half and fitted with a metal flange that allows the halves to be seprated to provide access to the interior. The interior surface was sandblasted and coated with a white latex paint having a reasonably constant diffuse reflectance over the visible spectrum. Although intended for application to building roofs, this paint looks promising as a candidate sphere paint, having the advantages over conventional integrating sphere paints of low cost and ease of application. The spectral reflectance of the coating is plotted in Fig. 3, as are the photopic sensitivity curve and spectral power curves for the sun and our electric source.

By removing material in the shape of a spherical cap, two sample ports were created (0.50 and 0.69 m in diameter). Four holes to receive sensors were arrayed around the port, at a distance of 58 cm from the port center. The sensors view the entire sphere except for the port, which is blocked by a small shield situated 7 cm from the sensor.

As shown in Fig.1, the sphere rides on a support mechanism capable of rotating the port about two perpendicular axes. Furthermore, the sample itself can rotate in the plane of the port about an axis perpendicular to the port. This allows us to obtain a full range of incidence angles relative to the port by altering the apparent altitude and azimuth of the source, which may be the sun or a suitable intense collimated electric lamp.

Preliminary measurements were made by locating around the port rim four silicon photodiode photometers having cosine and photopic corrections. The standard deviation of the average of these readings was sufficiently small (as expected in a sphere) to allow us to substitute a single sensor of the same type but having greater accuracy at the low illuminance levels that occur when testing devices having low transmittance.

To minimize costs, our initial source for indoor testing was a 450-W 28 V sealed-beam incandescent lamp (400,000 cp) operated by a voltage controller. The lamp beam has horizontal and vertical projections of 14 and 15 degrees, respectively. At a distance of 8 m it produces on the port an average illuminance of 2400 lux, with a ratio of standard deviation to average of $S.D./\langle E \rangle = 0.14$ (as measured by an array of 36 sensors over a port 0.69-m in diameter). It is possible to increase the distance to the source, thereby obtaining greater uniformity of incident flux over the port ($S.D./\langle E \rangle = 0.06$), and reducing available flux. Greater uniformity is advantageous when the device being tested has a transmittance that varies greatly over the port (e.g., an overhang that has a transmittance of unity over the unshaded portion of the port, and zero elsewhere).

As seen in Fig. 3, the overall spectra of lamp and sun differ markedly. However, the difference is not large in the spectral region where the photopic sensitivity is greatest. Furthermore, the sphere paint reflectance is fairly constant over this spectral region. We are investigating other electric sources that may have improved spectral characteristics, intensity, and/or collimation. Xenon and CSI sources are likely candidates.

EXPERIMENTAL PROCEDURE

Sphere measurements must be corrected for any stray light entering the port from other than the primary source. Measurements are normally made at night, since it is presently impossible to darken the room in which the sphere is located. Interreflected light from the source is another possible source of error. When measurements are made at night, background illuminance levels are typically less than 1% of the illuminance due to source plus background.

When it is necessary to subtract the background contribution, the illuminance in the sphere is measured twice with the sample in place: once with source and background illuminating the device, and once with the source shielded from direct view of the device. Subtraction of the two illuminance levels yields E, the illuminance due to the transmitted direct beam. Without changing the orientation of source and sphere, two similar measurements are made with the device removed from the sphere port, yielding E_0, the illuminance due to the direct beam transmitted by the open port. Illuminance measurements are normalized by the concurrent values of a monitor sensor (aimed at the lamp) in order to correct for source temporal instability. (This is a proxy for the ratio ρ_0/ρ appearing in Eq. 1). Equation 1 is then used to calculate the device's transmittance $T(\theta,\phi)$ for the chosen source position (θ,ϕ).

RESULTS

The results of measurements for some conventional and novel devices are shown in Figs. 4 through 8. Figures 4 and 5 compare measured transmittance versus angle of incidence for clear and heat-absorbing glass samples to the respective transmittance values calculated from nominal optical constants.

Figure 6 shows the transmittance of "micro-louvered" sun screens approaching zero for incidence angles greater than about 40^{o}. In application, however, skylight and ground-reflected light must also be considered. The transmittance for these diffuse quantities can be determined by appropriate integration of directional-hemispherical properties. Further measurements, using the LBL artificial sky,[2] should clarify the complete transmittance behavior of these devices.

Figure 7 contrasts the performance of two venetian blinds, and indicates the effects of slat tilt angle and reflectance (color). Computer modeling of sophisticated daylighting applications of venetian blinds requires a data base of performance versus sun position, slat angle, and reflectance. The LBL scanning photometer/radiometer (under development) will complement the integrating sphere in determining venetian blind performance by directly measuring the bi-directional transmittance.

Because only the area in a building within immediate proximity (about 5 m) of a window or skylight receives daylight reliably, light guides have been considered one means of increasing the penetration of daylight into buildings. Figure 8 compares the transmittance of three mirrored light guides having identical cross sections but different lengths. Further research is underway on light guides having different cross-sectional shapes, as well as input-enhancers (focusers) to increase the available input flux. Some of these guides will "turn corners" in order to transfer light flux in arbitrary directions within a building.

SUMMARY

Preliminary measurements with the integrating sphere have demonstrated its utility for measuring the directional hemispherical transmittance of a wide range of fenestration systems, including some novel devices of unusual and/or cumbersome shape. We note that this approach to characterizing fenestration transmittance is analogous to measurements of the luminous output of electric lamps. Each combination of window element plus sun and/or sky must be treated as a potentially different light source. Other work in progress in our research program extends the anology to the bi-directional transmittance of a window system, which we interpret (and measure) as the candlepower distribution from a light fixture. Future research will concentrate on developing a data base of experimentally derived parameters characterizing the performance of fenestration components. This will be used with illuminance and energy simulation models to allow more accurate prediction of the energy-related impact of fenestration on both the thermal and lighting performance of buildings.

ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

1. Selkowitz, S. 1983. New Tools for Analyzing the Thermal and Daylighting Performance of Fenestration in Multistory Buildings, presented at the International Symposium on the Design of Multistory Buildings for Physical and Environmental Performance, Sydney, Australia, June 1-3, 1983. Lawrence Berkeley Laboratory Report, LBL-16154.

2. Selkowitz, S., MacGowan, D., McSwain, B., and Navvab, M. A Hemispherical Sky Simulator for Daylighting Studies: Design, Construction, and Operation. Submitted to IES Annual Technical Conference, September 1981. Lawrence Berkeley Laboratory Report, LBL-12967 (Draft).

3. Walsh, J.T. 1958. The Principles of Photometry. New York, N.Y.: Dover Publications, Inc., p. 258.

4. Hisdal, B.J. 1965. Reflectance of Perfect Diffuse and Specular Samples in the Integrating Sphere. Journal of the Optical Society of America, 55, September:1122-1128.

5. Hisdal, B.J. 1965. Reflectance of Nonperfect Surfaces in the Integrating Sphere. Journal of the Optical Society of America, 55, October:1255-1260.

6. Zerlaut, G.A., and Anderson, T.E. 1981. Multiple-Integrating Sphere Spectrophotometer for Measuring Absolute Spectral Reflectance and Transmittance. Applied Optics, 20, November:3797-3804.

7. Symons, J.G., Christie, E.A., and Peck, M.K. 1982. Integrating Sphere for Solar Transmittance Measurement of Planar and Nonplanar Samples. Applied Optics, 21, August:2827-2832.

8. Boyd, R. A. 1951. The Development of Prismatic Glass Block and the Daylighting Laboratory. Engineering Research Bulletin, No. 32. Engineering Research Laboratory, University of Michigan.

9. Kessel, J. 1984. Transmittance Measurements in the Integrating Sphere. Lawrence Berkeley Laboratory Report, LBL-17807. Draft, January 1984.

10. Walsh, ibid, p. 421-423.

The Discussion and Rebuttal sections that follow resulted from this paper's presentation at the IES conference. When papers are presented before the IES, opportunity is provided for comments and discussion, which are considered part of the paper. The following Discussion and

Rebuttal are provided here for interested readers.

DISCUSSION

A. R. Robertson (National Research Council of Canada, Physics Division). The use of integrating spheres to measure directional-hemispherical transmittance is a common technique but most instruments of this type are suitable only for measuring small samples of a few centimeters in diameter. In this paper, Kessel and Selkowitz describe an apparatus with a 2-meter-diameter sphere capable of measuring the transmittance of a 50- or 69-centimeter area of full-scale window systems.

The sensor in the present apparatus is a photometer with a photopic $V(\lambda)$ sensitivity. It would be simple to replace the photometer by an infrared-sensitive radiometer so that measurements of infrared transmittance could also be made. I hope that the authors plan to do this. Ultraviolet measurements would also be useful in some applications. Modification of the apparatus to make these measurements would be more difficult, because the sphere paint would have to be changed, but nevertheless would be worthwhile.

The apparatus uses a single beam. Have the authors considered double-beam operation? This would involve directing a second beam from the source through a second opening in the sphere to provide a reference signal. Measurements with the sample in place and with the main port open would both be made relative to the signal generated by the reference beam. This would automatically compensate for the change in sphere efficiency caused by reflections from the sample and would thus eliminate the need for a subsidiary measurement of the reflectance of the sample.

The authors have correctly included a shield to prevent the sensor from receiving light directly from the sample port. This is important for accurate measurements, but is often overlooked.

I congratulate the authors on a very clearly written paper and on designing and building an apparatus which is capable of producing much useful information on the transmittance of pratical window systems.

D.L. DiLaura, (Lighting Technologies of Boulder Colorado). The authors are to be commended for a clear paper detailing a process for the acquisition of important information. Answers to a number of questions might help clarify some minor points: a) How (if at all) was the effect of the screen inside the sphere taken into account when determining the transmittance? b) Can the authors offer a suggestion as to the size of the effect of the rather wide difference that exists between the spectral composition of their electric source and sunlight? c) Why is there an increased difference between measurements and calculations for clear glass when the incident angle is between 40 and 60 degrees?

Agreement is very very good at 30 and 70 degrees. Is this a polarization effect; Brewster's angle being approximately 55 degrees for typical flat clear glass?

Vic Crisp. The authors have presented what appears to be a detailed and rigorous approach to the problem of measuring and characterizing the transmission properties of window systems. There is little doubt that there is a need for such an approach since the alternative, i.e., calculation, becomes rapidly unattractive once the window system has become even moderately complex in terms of the number of occluding and/or reflecting surfaces involved.

However, it is not clear how the information gathered using this particular approach will be used. The information produced is, in fact, most suitable for some kind of lumen method (or gross flux) approach to say window sizing, as is likely to be used in the UK's forthcoming CIBS window guide (1) based on an earlier proposal by Lynes (2) . To do this the appropriate thermal properties of the window systems also need to be determined. Does the LBL program include measurements of such properties?

The more subtle effects of windows such as their implications for the appearance of the daylit space and the integration of electric lighting with that daylight through appropriate lighting controls, almost certainly require a knowledge of the directional properties of the transmitted light from the window system rather than the gross flux. The authors might care to comment on how they see the measurements they have described eventually fitting into a 'designers package'.

Finally, on a somewhat trivial point, can we assume that 'angle of incidence' in Figs. (6), (7) and (8) corresponds to altitude at zero azimuth from Section II and Figure 1?

(1)Crisp and Littlefair, Average daylight factor prediction. Proceedings CIBS National Lighting Conference, Cambridge UK 1984.

(2)Lynes, A sequence for daylighting design. LR & T 11 (2) 1979.

REBUTTAL

Authors: The reviewers raise several questions and points of clarifications to which we are pleased to respond.

Mr. Robertson suggests replacing the photometric sensor with a radiometric detector or UV detector. We do plan to use both radiometric and photometric detectors in future work because we are interested in total solar transmittance as well as visible transmittance. We have not planned to make UV measurements since they are not normally useful for daylighting or thermal building energy analysis. Such measurements may, however, prove useful when material degradation effects, or human health effects, are considered. If a suitable source, detector and sphere paint were utilized, the measurements could be readily made. We decided to use a single beam rather than a double beam configuration due in part to the practical difficulties of building light sources with adequate collimation, and uniformity over the port. We concluded that the adjustment for sample back reflectance in the single port design was relatively simple in most cases.

Mr. Robertson emphasizes the importance of a shield to prevent the sensor from receiving light directly from the sample; Mr. DiLaura asked how its effect is accounted for in determining transmittance. The shield is designed to just block the sensor view of the port--it will otherwise not interfere with the sensor field of view in the sphere. Under these conditions, and with the shield in place for both the open port and a test device the effect should be negligible. We verified this by comparing test device transmittance for several sensor locations and shield designs and found no measurable effects. We used an incandescent lamp as our source in the initial phases of this project because it met our uniformity and collimation requirements at very low cost. Our intent has always been to substitute an appropriate arc lamp with a spectral distribution close to that of the sun. Several such sources are now being evaluated. Since we use a photometric detector with good photopic correction and have primarily tested materials and devices without selective spectral properties, the use of the incandescent lamp does not introduce substantial error. However, when we make radiometric measurements of selectively transmitting materials (e.g., blue-green absorbing glass or coated glasses) the spectral output of the source will affect results. We have moved the sphere outdoors and used the sun as a source, but generally prefer the electric source for its control, ease of use, etc. Note that the sun's spectral output will change noticeably with solar altitude and atmospheric conditions.

We have no immediate explanation for the differences in measured vs. calculated glass transmittance between 40 and 60^{o} incident angle. The calculations were done using nominal glass optical properties. We plan to compare the sphere results to direct measurements of the same sample in a spectroradiometer.

Mr. Crisp is correct in noting that the angle of incidence data in Figs. (6), (7) and (8) corresponds to the altitude at zero azimuth. We have measured venetian blind transmittance at many combinations of altitude and azimuth, as well as slat tilt angle. The data from such testing is voluminous, so we chose to show only the zero azimuth case here.

Mr. Crisp raises two very important points on thermal properties and directional properties of transmitted light that we are pleased to be able to comment on here. One use for the transmittance data is a lumen method or coefficient of utilization calculation. We are working on a new version of this approach for daylighting that uses separate sun (angle dependent), sky diffuse, and ground diffuse features; so that the transmittance for each flux condition must be determined separately. For energy analysis, it is necessary to predict total solar heat gain, which requires not only solar transmittance (measured in our sphere using the radiometer), but reflectance and absorptance as well.

We are developing other measurement and calculation procedures to generate these data as described in (1). We are also now field testing an outdoor window test facility that will allow us to validate the accuracy of these computations and laboratory measurements (2).

The directional properties of transmitted light are critical for any assessment of lighting quality and illuminance distribution in a room. We have developed and are now calibrating a scanning luminance meter to measure the directional-directional transmittance of window systems (1). Data collected from this measurement system will allow us to generate a candlepower distribution curve for each complex window system. This in turn will allow the daylight emitted from complex window systems to be treated in room lighting calculatons as if it was emitted from a luminaire. This process is analogous to the use of a goniophotometer to characterize the candlepower distribution of a luminaire.

We envision the sphere and the scanning photometer as instruments to create large data bases of measured optical data on a range of generic fenestration devices. These will be stored as data libraries in computerized illuminance models and building energy analysis models and accessed as required by designers. Given the trends in microcomputers, very large libraries of data are stored and accessed much more quickly than complex calculations of light transmission can be completed. For research purposes, the two facilities are valuable tools to characterize new optical materials and devices.

We appreciate the reviewers interest in this work and look forward to presenting additional results in future papers.

(1) S. Selkowitz, New Tools for Analyzing the Thermal and Daylighting Performance of Fenestration in Multistory Buildings, May 1983. Presented at the International Symposium on the Design of Multistory Buildings for Physical and Environmental Performance, Sydney, Australia, June 1-3, 1983. Lawrence Berkeley Laboratory Report 16154.

(2) J. H. Klems, Measurement of Fenestration Net Energy Performance: Considerations Leading to Development of the Mobile Window Thermal Test (MoWiTT) Facility, May 1984. Submitted to the Journal of Solar Energy Engineering. Lawrence Berkeley Laboratory Report 17943.

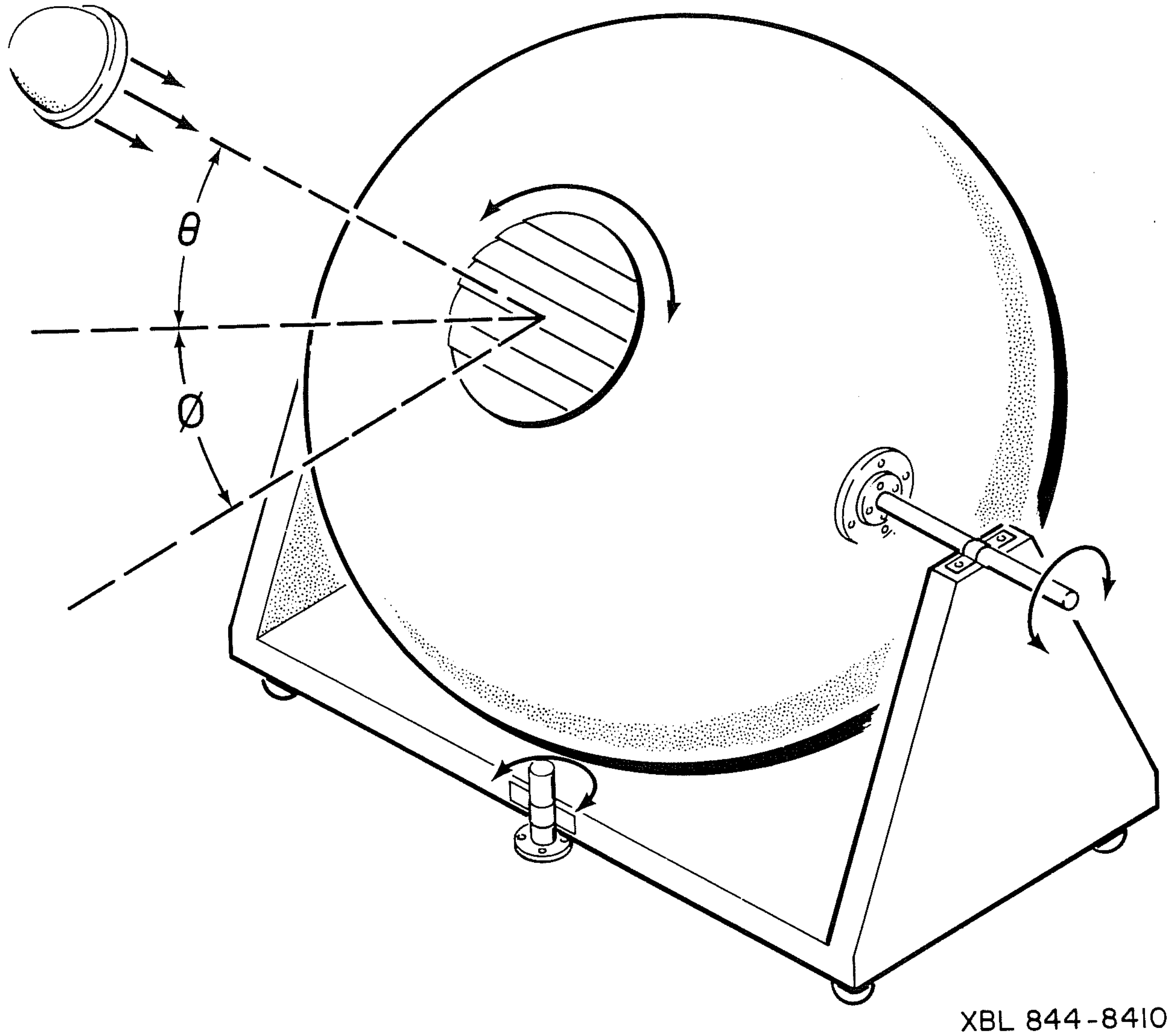

Figure 1. Experimental arrangement illustrating source position and rotational axes.

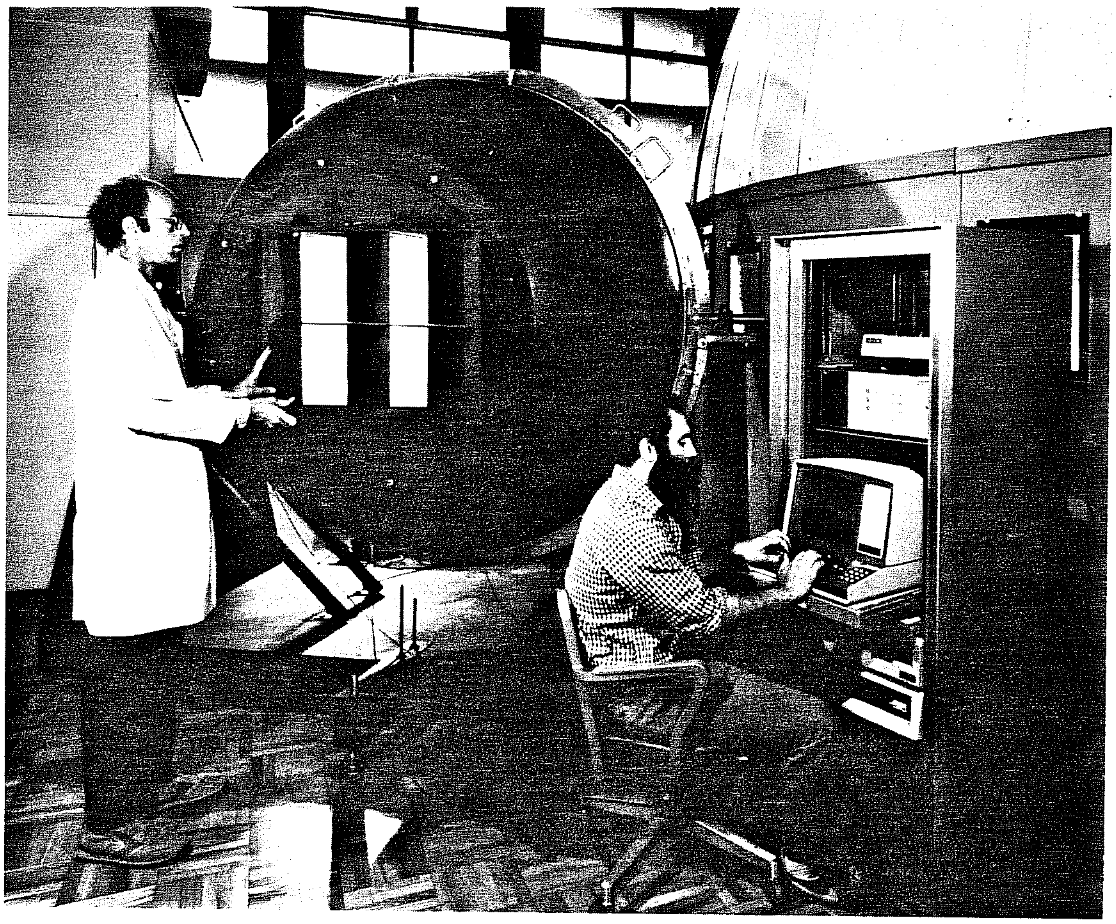

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Figure 2. The sphere in use.

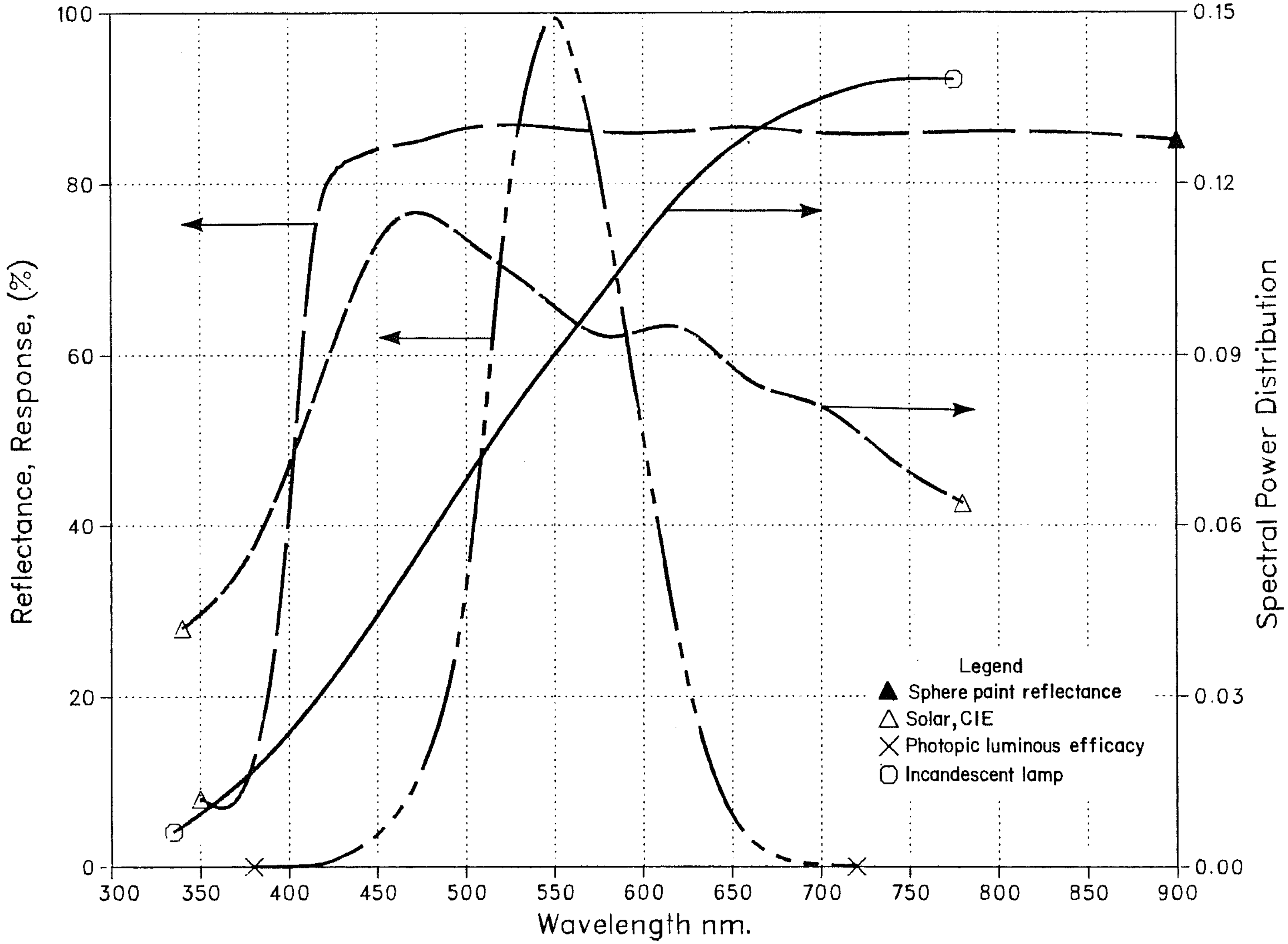

Figure 3. Spectral characteristics of paint, eye, lamp, and sun.

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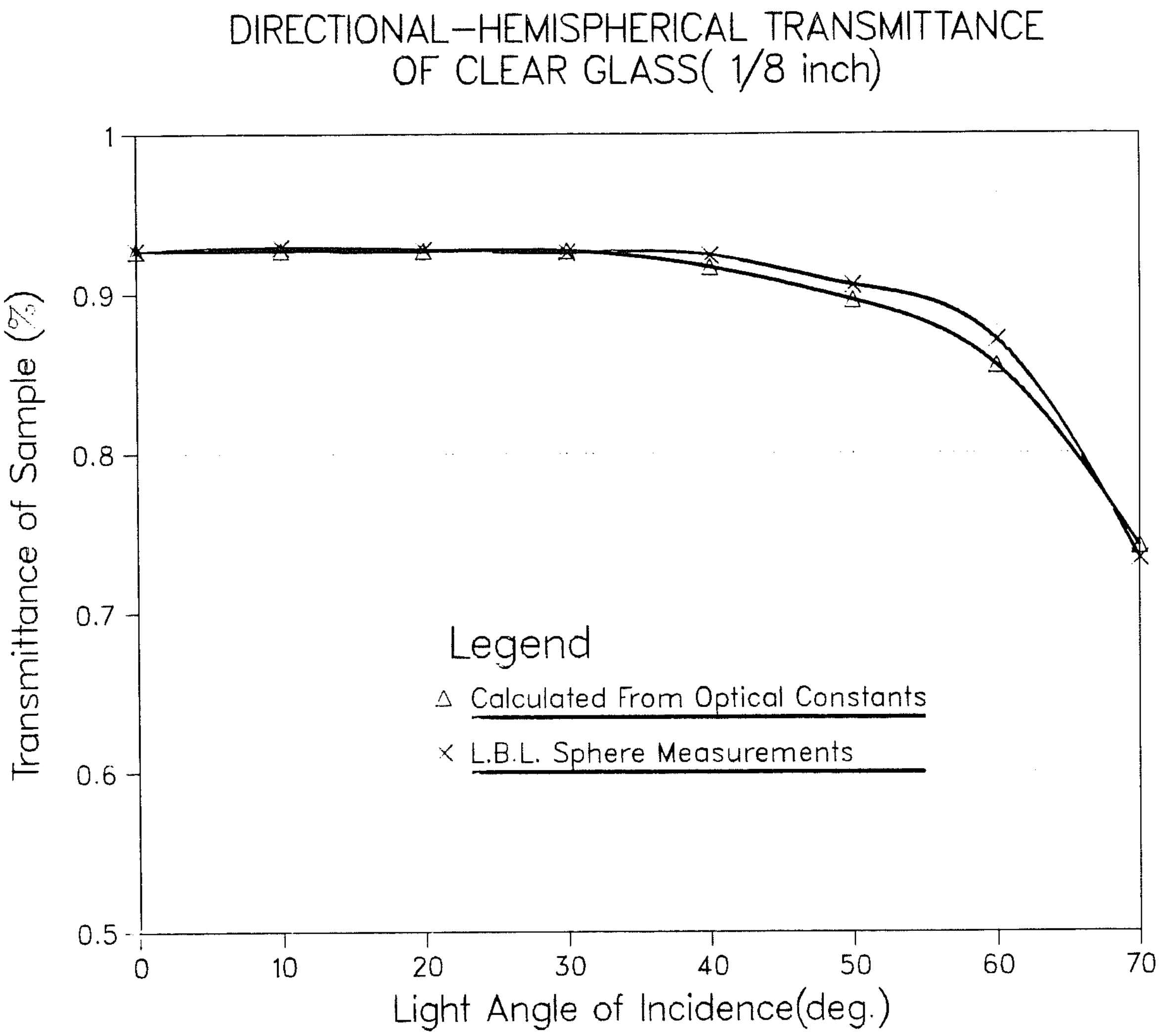

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Figure 4. Transmittance of 1/8-inch clear glass.

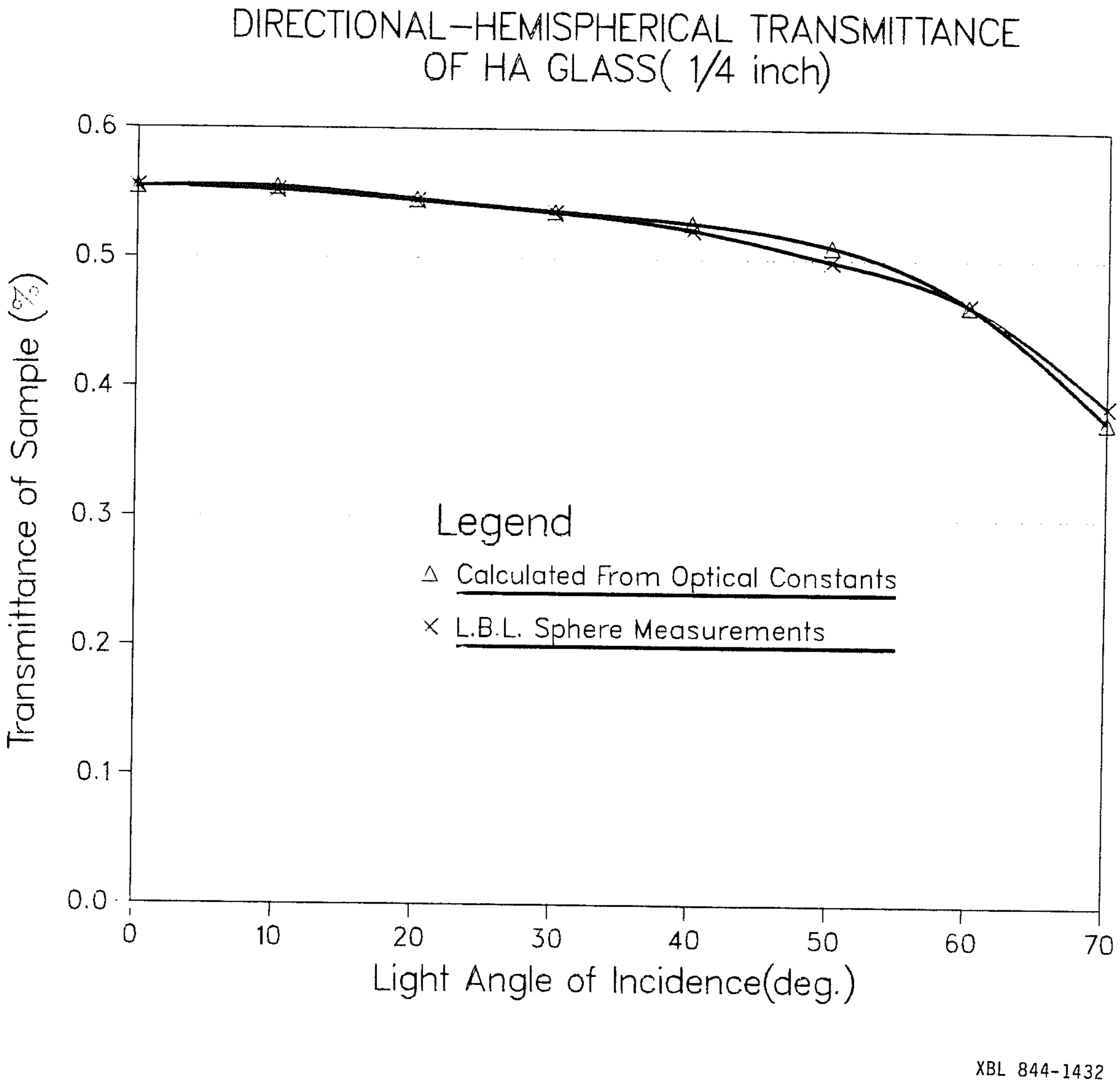

Figure 5. Transmittance of 1/4-inch HA glass (bronze).

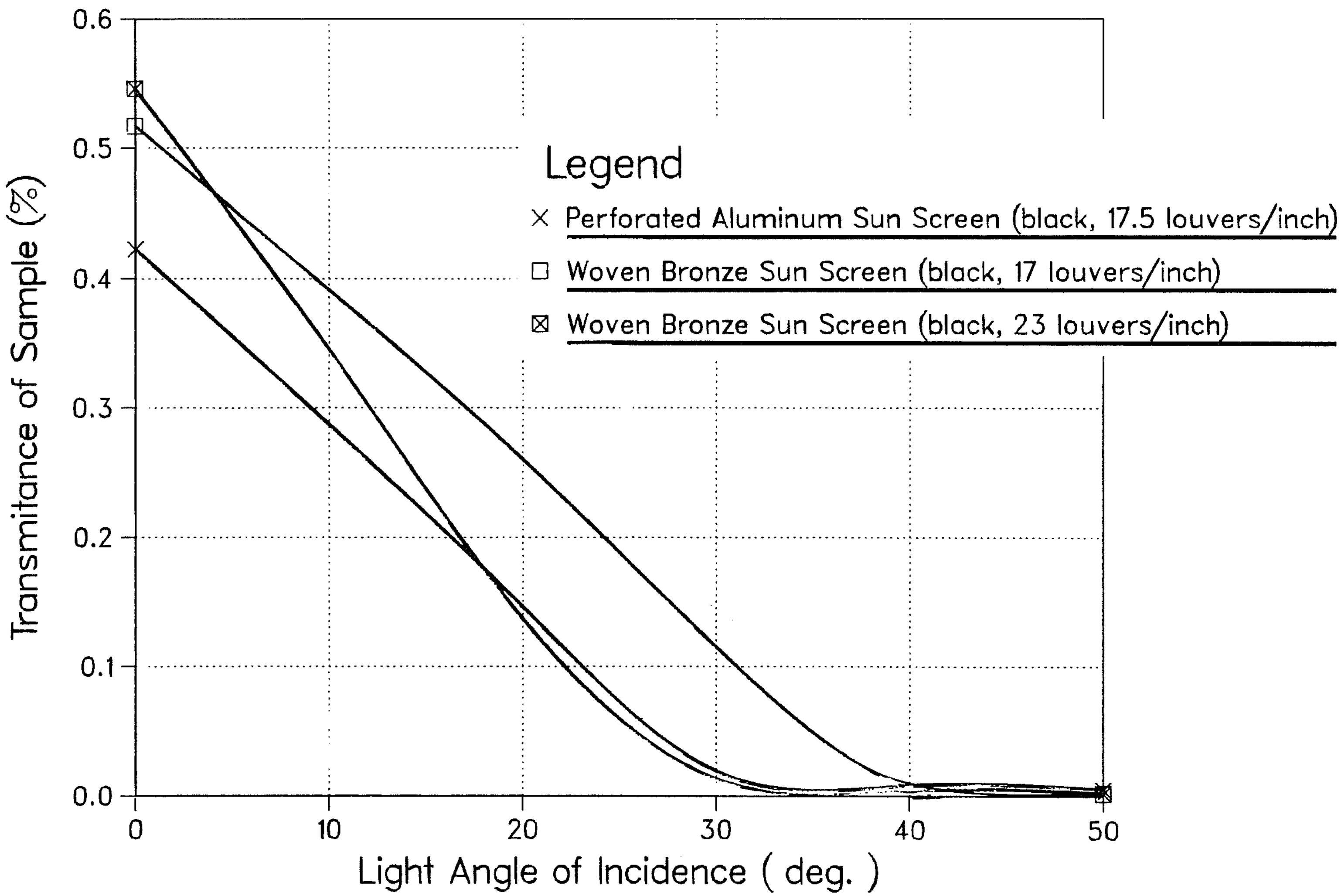

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Figure 6. Transmittance of "micro-louvered" devices.

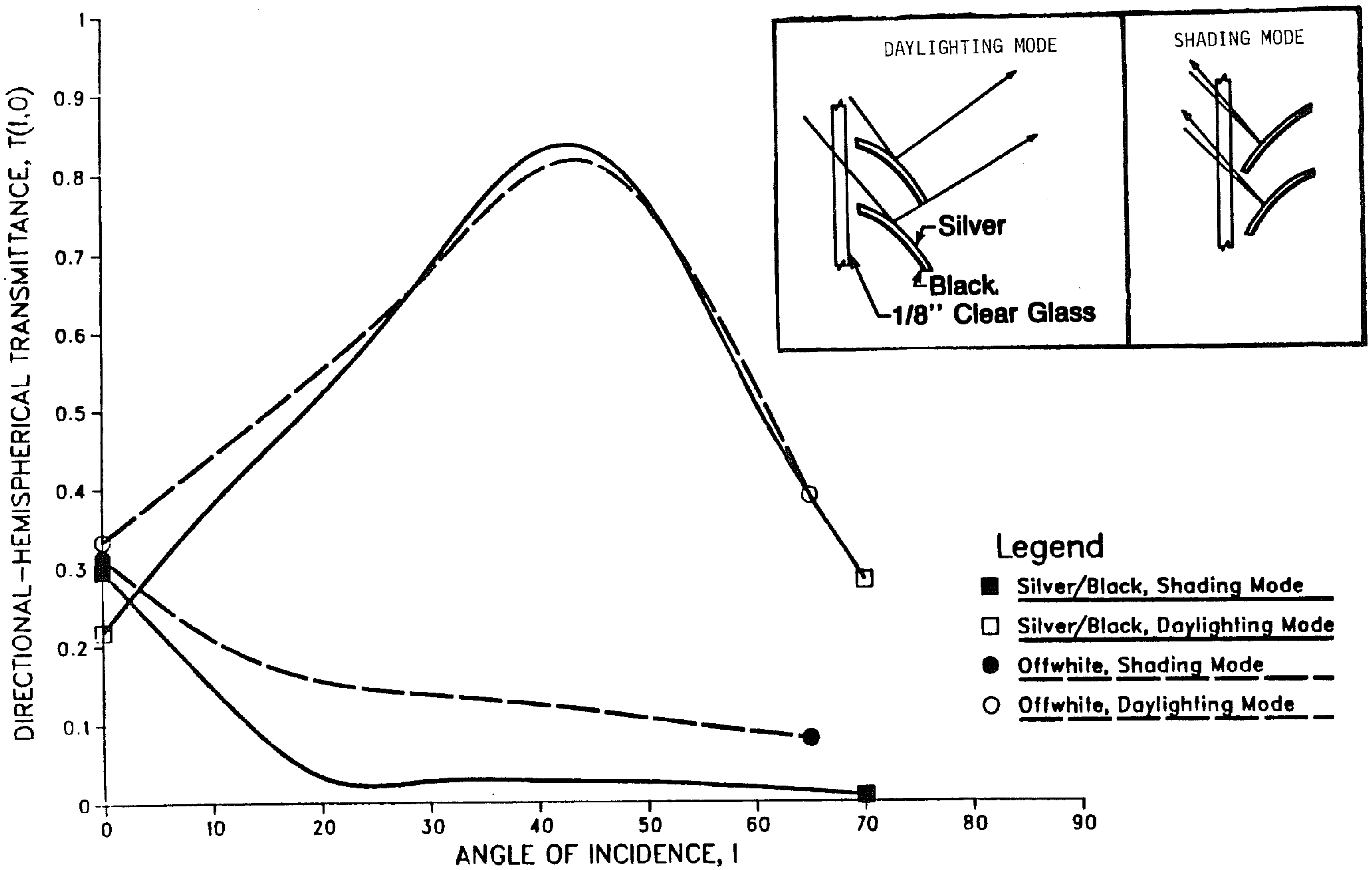

Figure 7. Transmittance of two venetian blinds.

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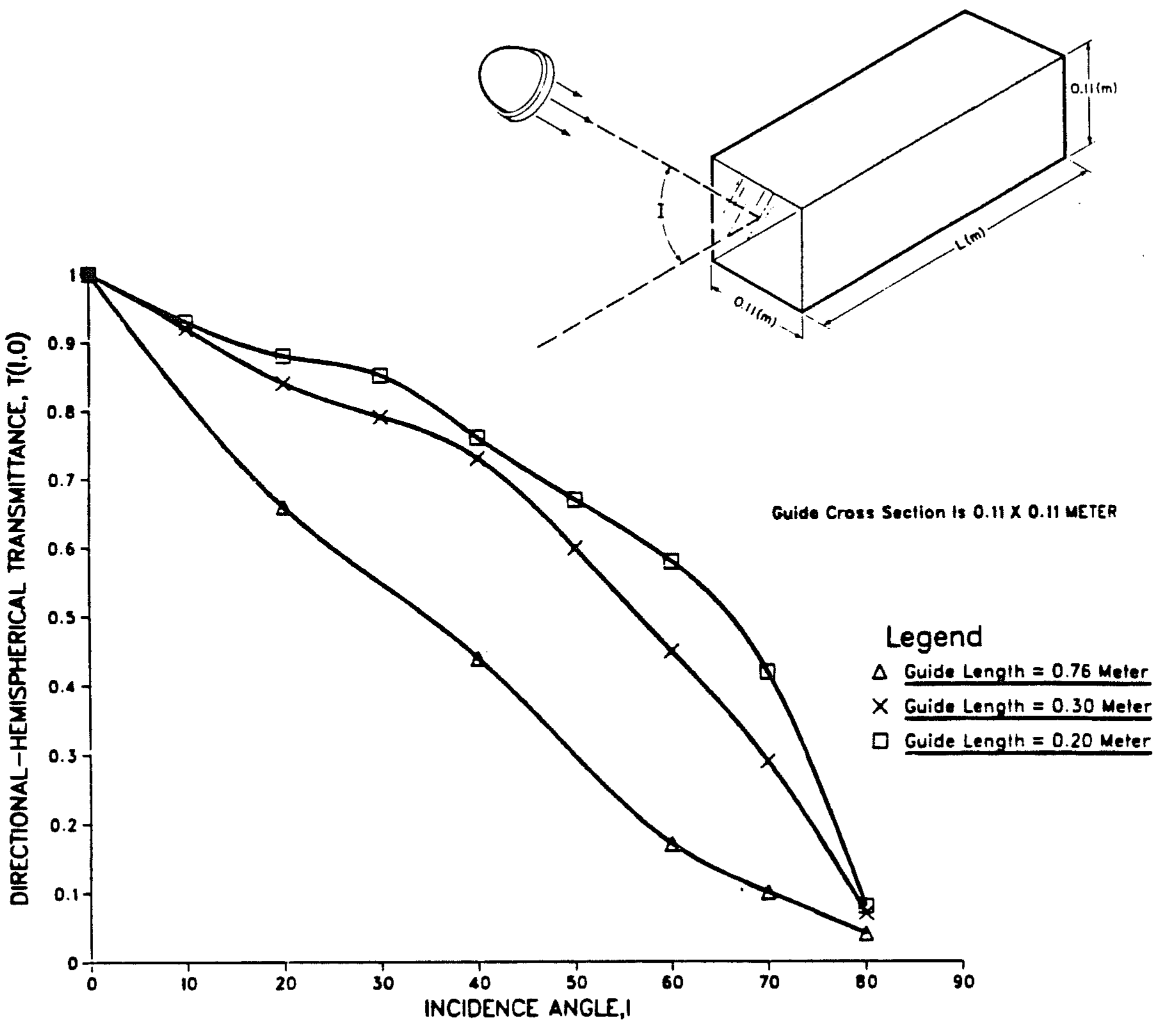

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Figure 8. Transmittance of three mirrored light guides.